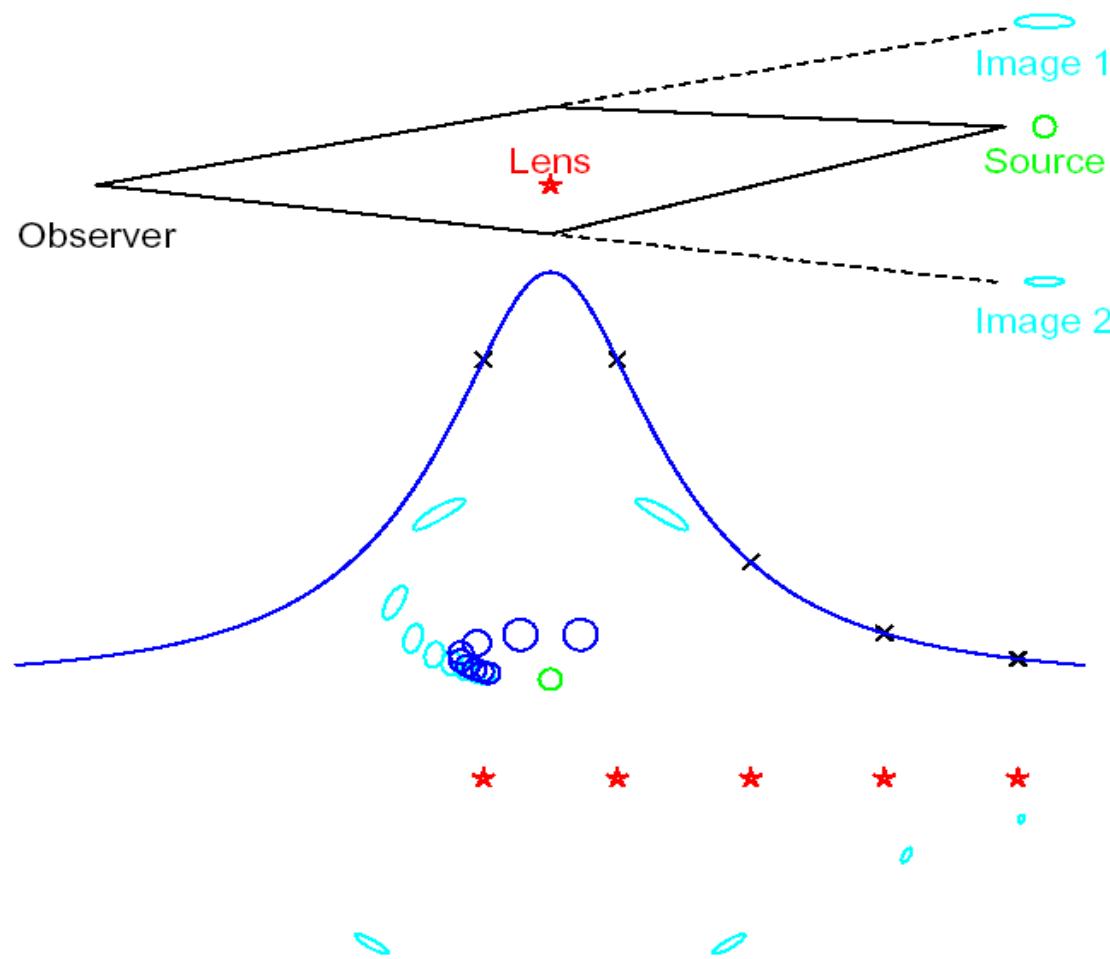


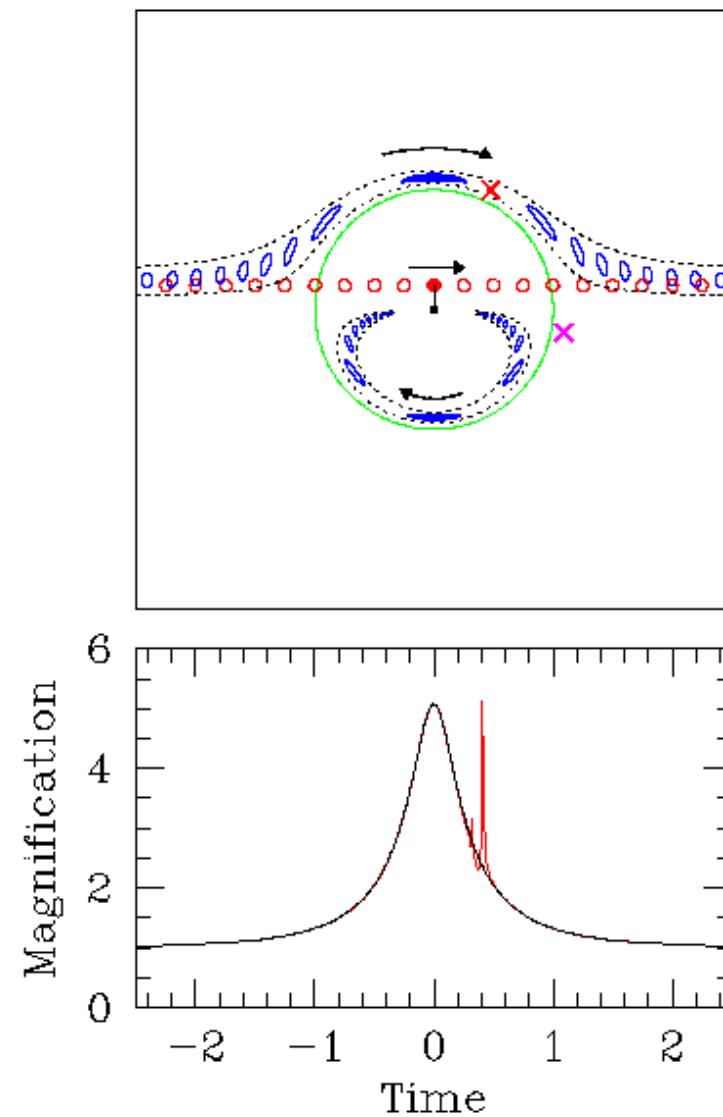
Microlensing: Results and Prospects

From the Ground

Andy Gould (Ohio State)



How Microlensing Finds Planets



Microlensing: Generation 0

Abandoned Child

- Einstein 1936a, Science, 84, 506

“Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request there is no great chance of observing this phenomenon.”

- Einstein 1936b (private letter to Science editor)

“Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy.”

Generation - 1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]

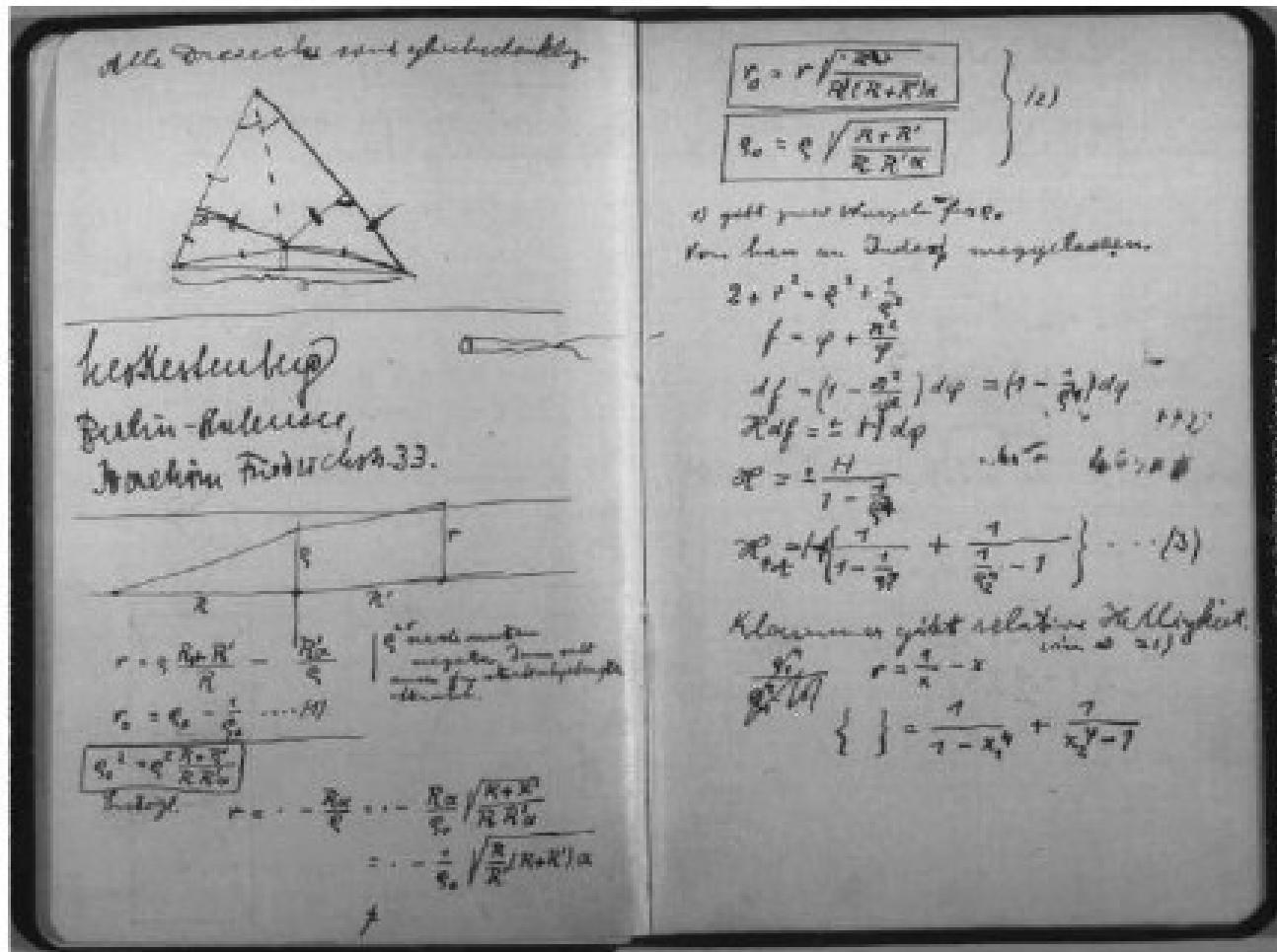


Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein's scratch notebook [12]. [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem.]

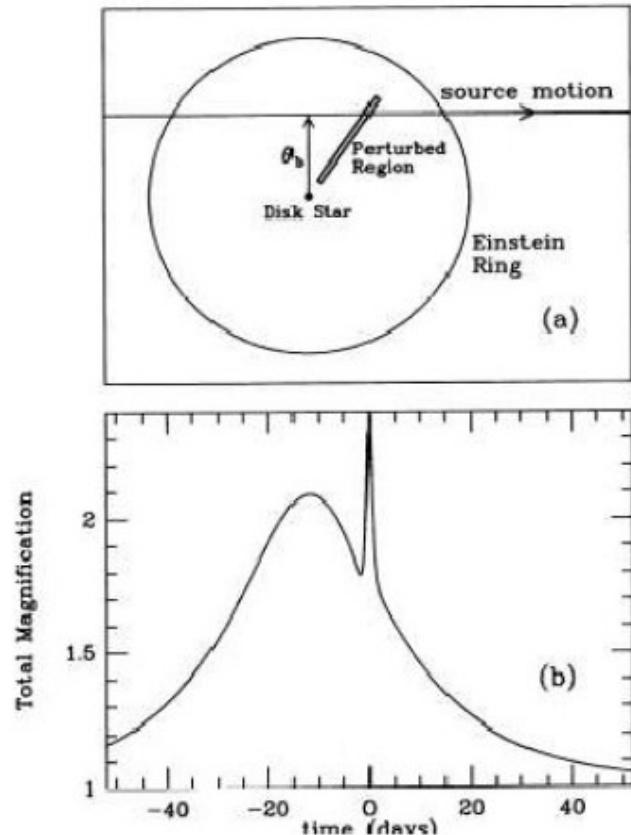
Theory: Combine Survey with Followup

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

ANDREW GOULD AND ABRAHAM LOEB

Institute for Advanced Study, Princeton, NJ 08540

Received 1991 December 26; accepted 1992 March 9



5. OBSERVATIONAL REQUIREMENTS

Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

While observations from one site would be useful, there are advantages to be gained by observing from several sites. First, two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,

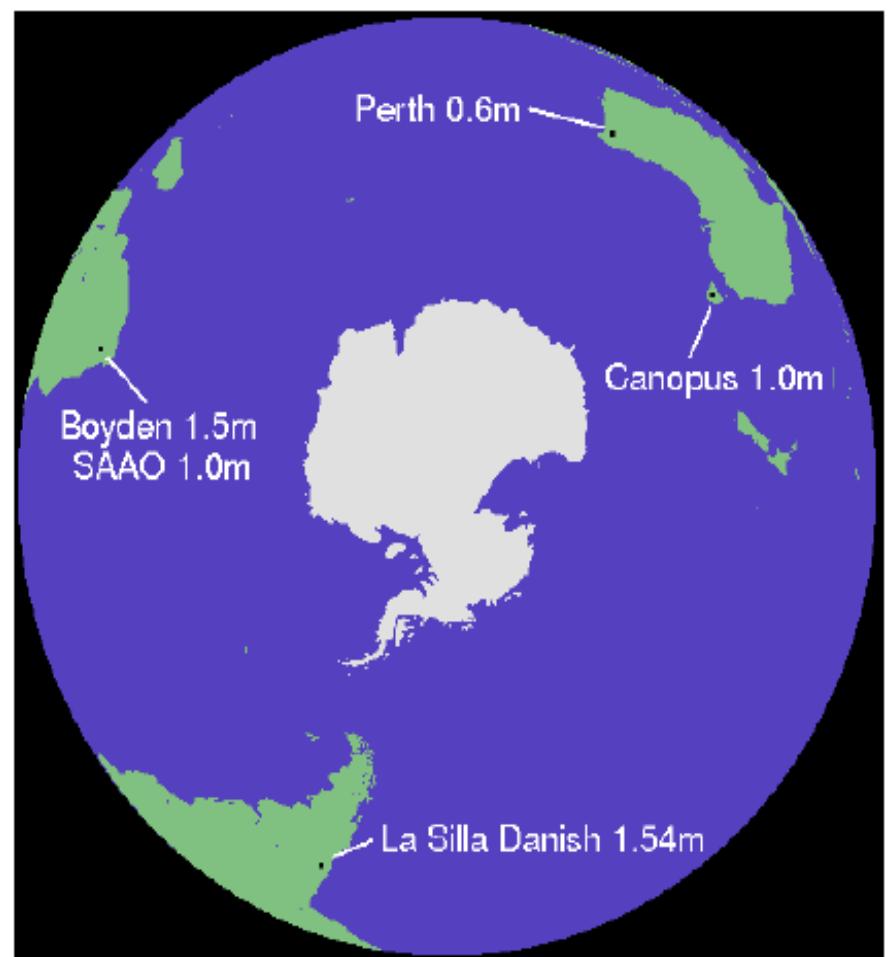
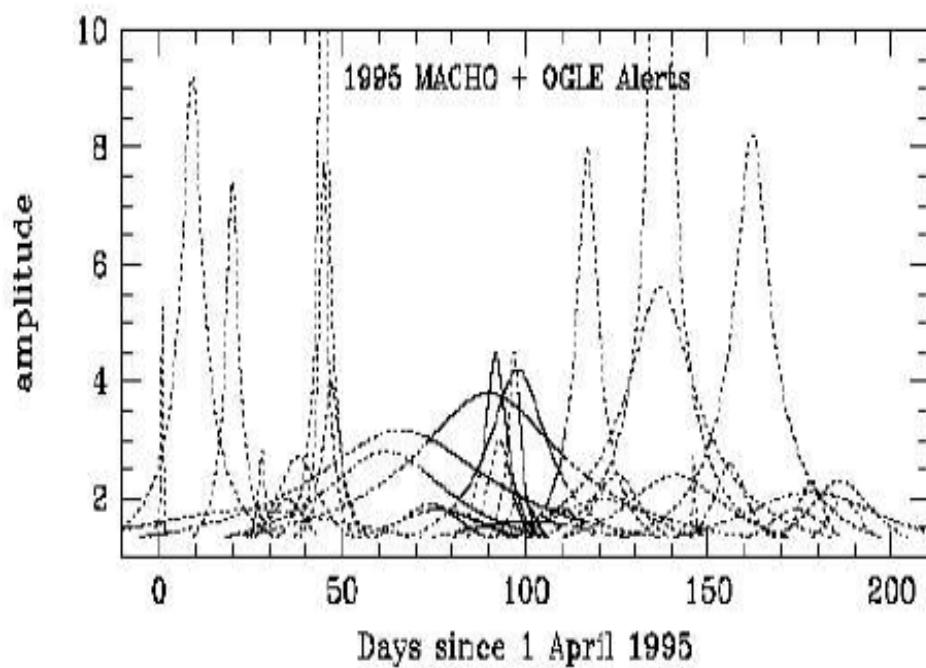
==> Practical Plan

- Penny Sackett
- Use existing underutilized 1m's to followup alerts from existing (MACHO + OGLE) Surveys



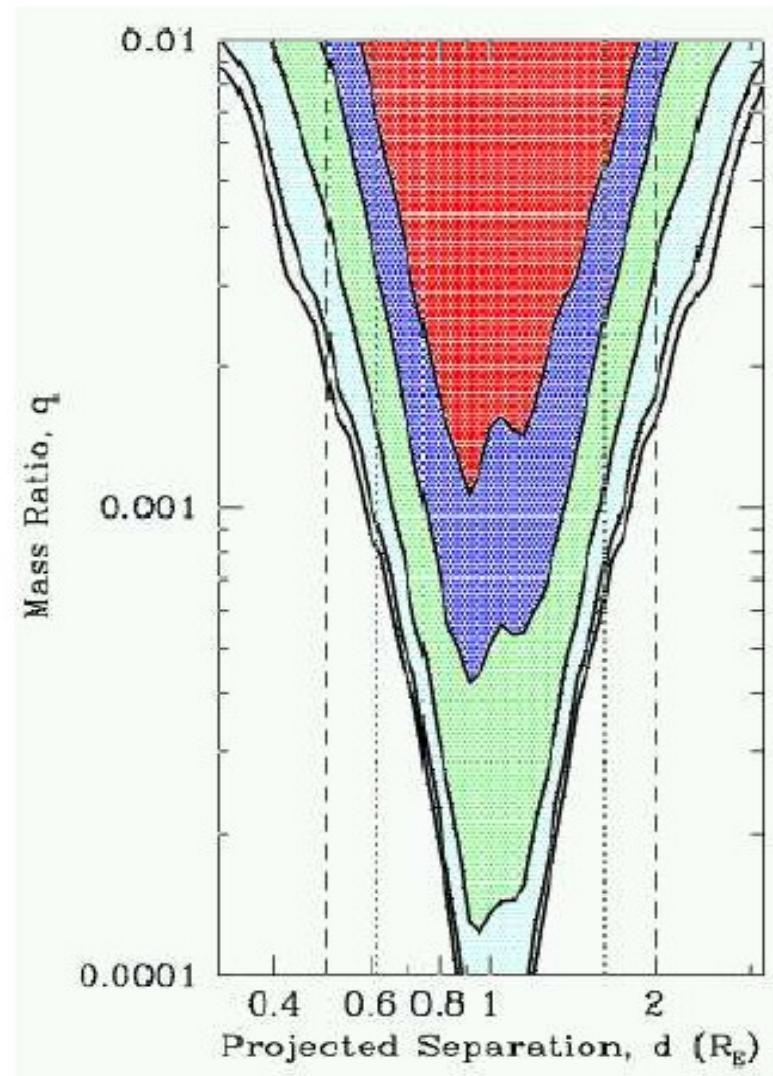
1995 PLANET Pilot Season

- Albrow et al. 1998
- ApJ, 509, 687



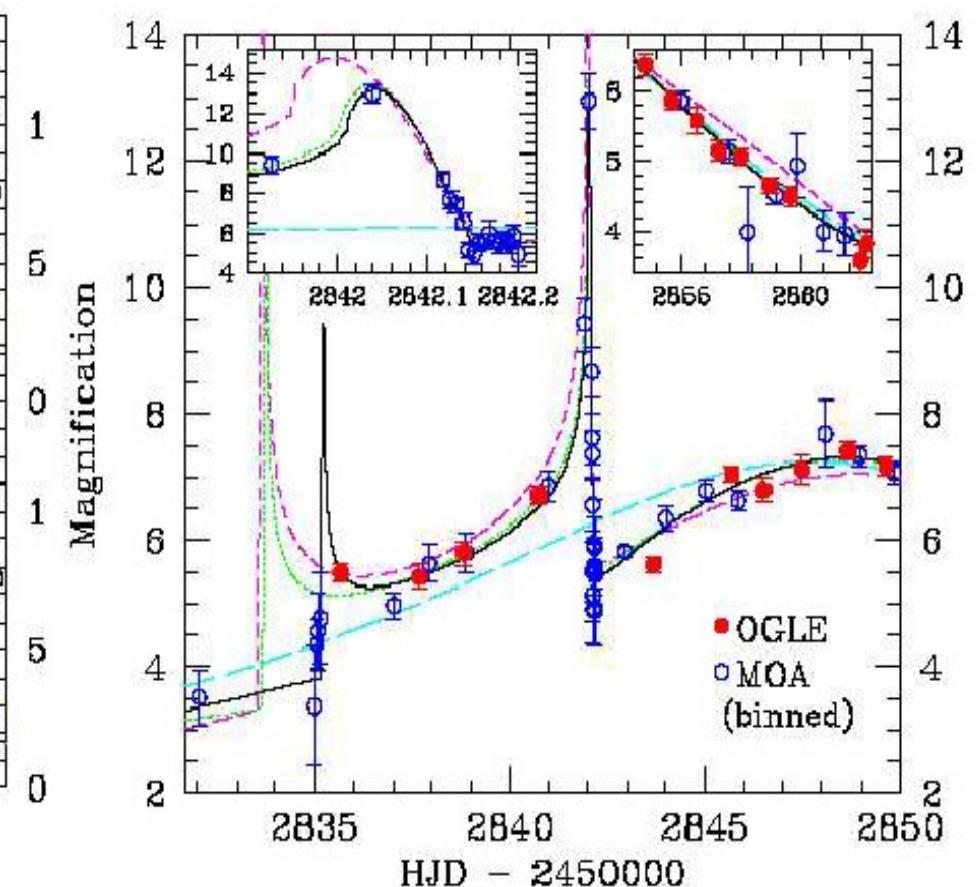
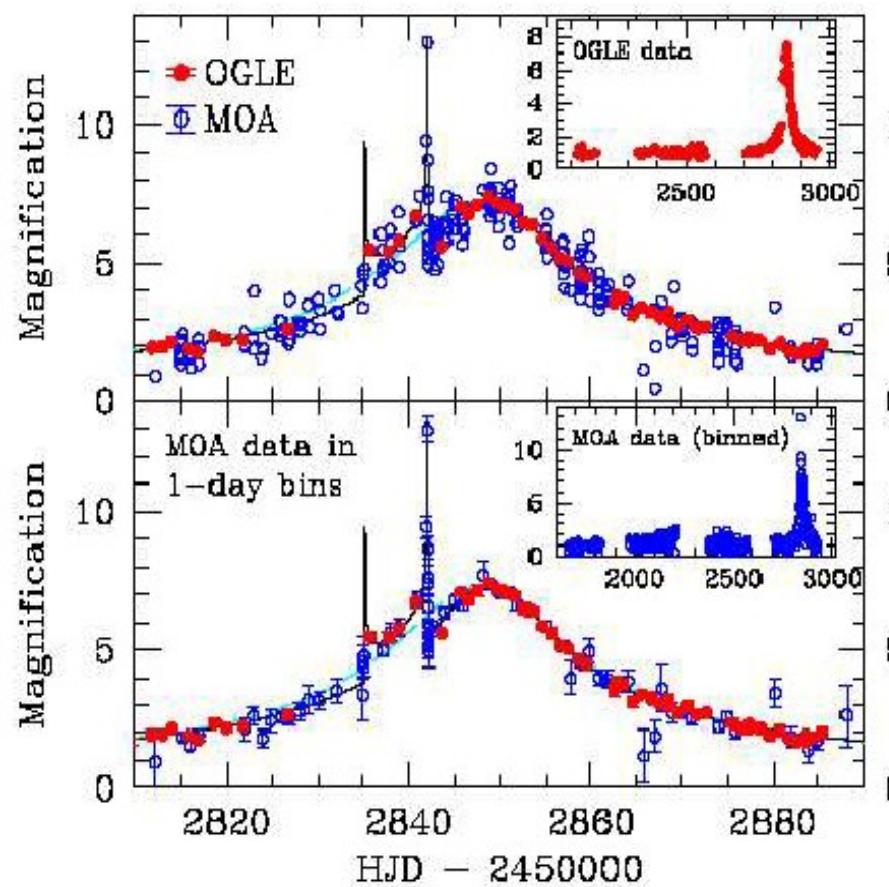
5 Years Later: Nada

- Gaudi et al. 2002,
ApJ, 566, 463
- Microlensing Constraints
on the Frequency of
Jupiter-Mass Companions:
Analysis of 5 Years of
PLANET Photometry
- 43 Events!

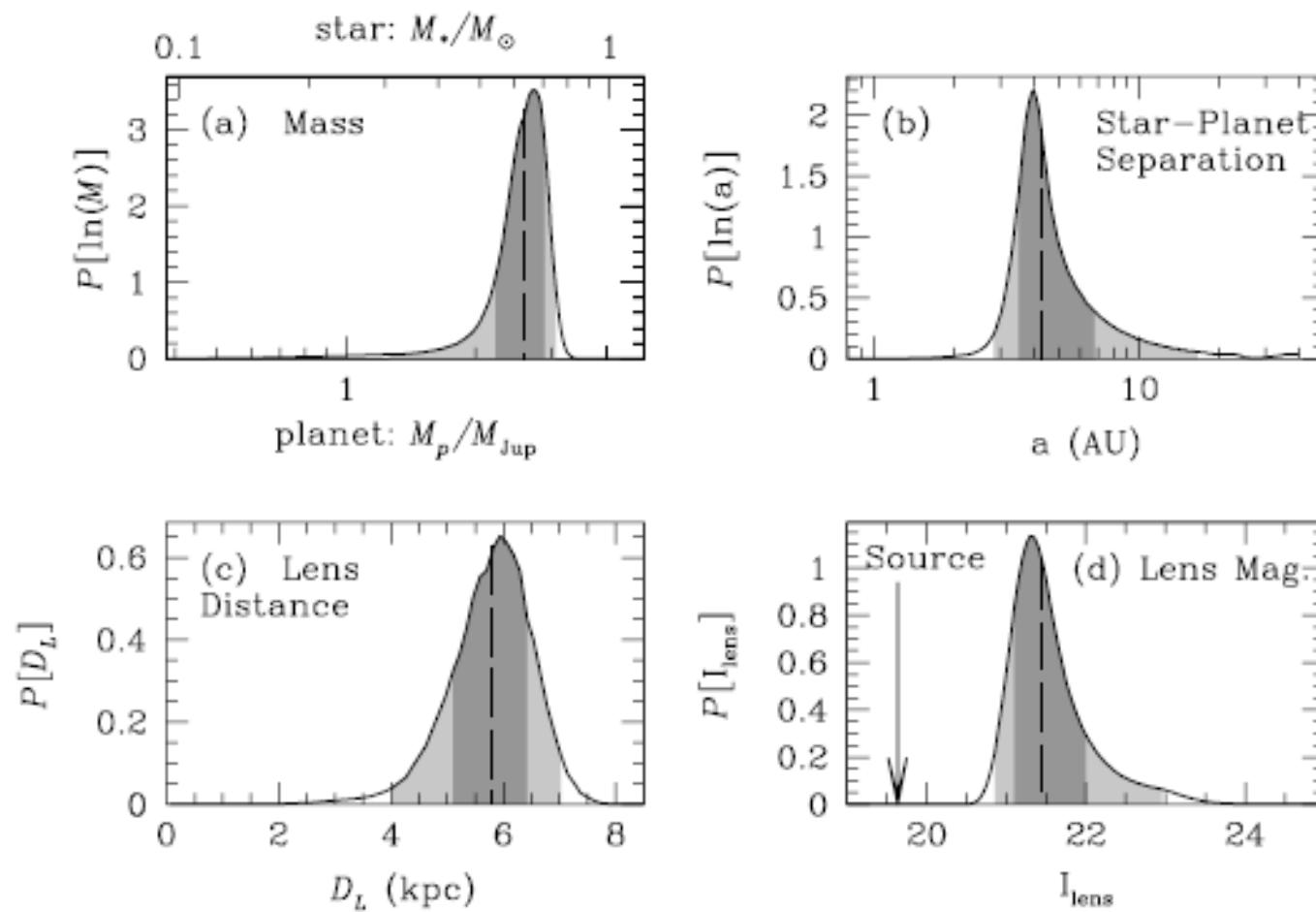


OGLE-2003-BLG-235/MOA-2003-BLG-53

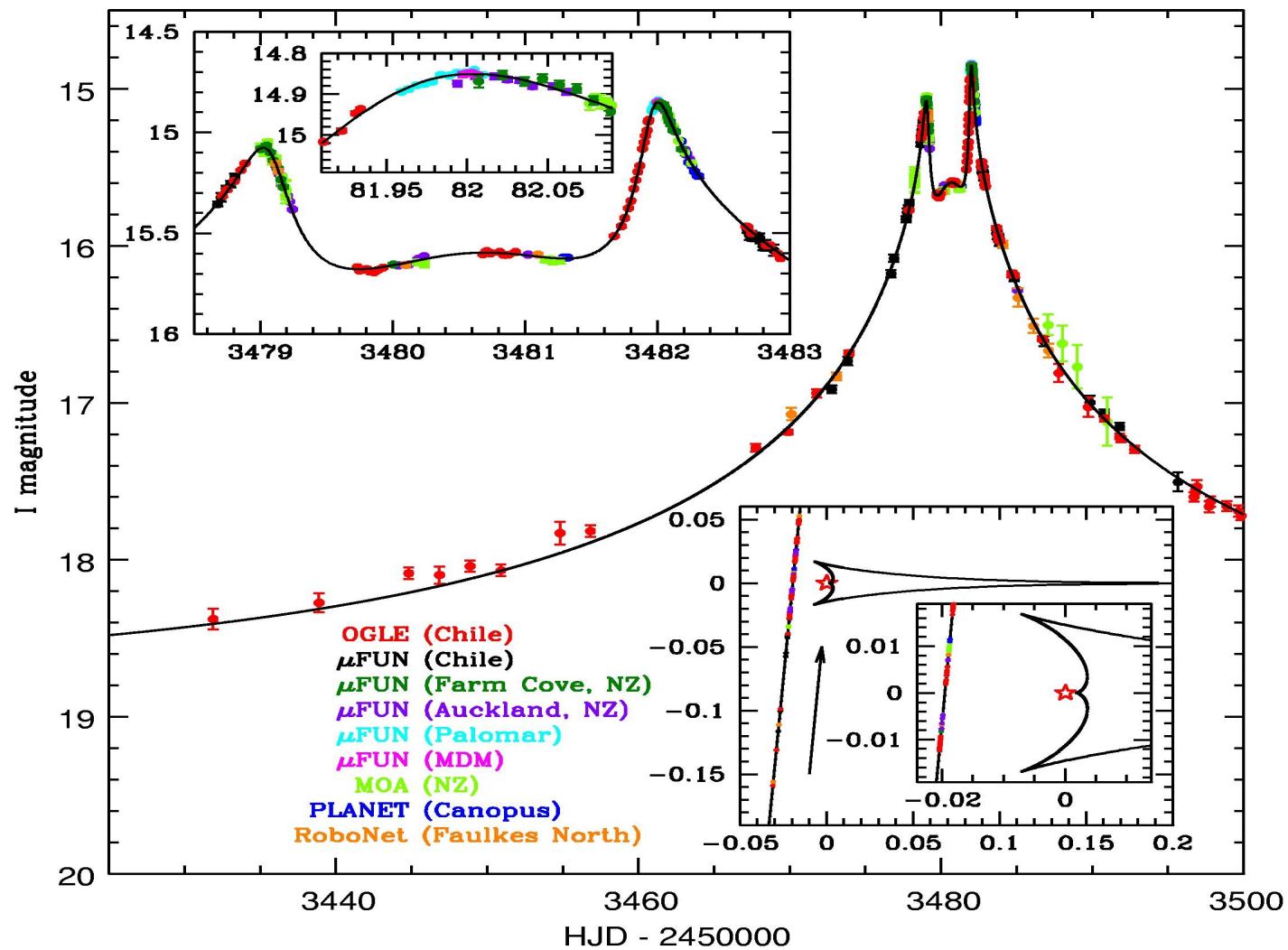
“Pure-Survey” Detection



Planet/Star Characteristics Reasonably Well-Determined



2nd Microlensing Planet



OGLE-2005-BLG-071: Really a Planet?

$\Delta t(\text{caustics}) \sim 3 \text{ Days}$

Chang–Refsdal: $\Delta u \sim 4q/b^2$

$$\Delta u = \Delta t/t_E$$

From Lightcurve: $t_E > 40 \text{ days}$

From Wiggle: $b \sim 1$

$$q \sim (\Delta t/t_E)b^2/4 < 0.019 \quad b^2 \sim 0.03$$

Udalski et al. 2005, ApJ 628 L109:

$$q = 0.007, b=1.29, t_E=71 \text{ days}$$

The New Zealand Connection

Grant, Ian, Jennie, Phil



Amateurs + Professionals

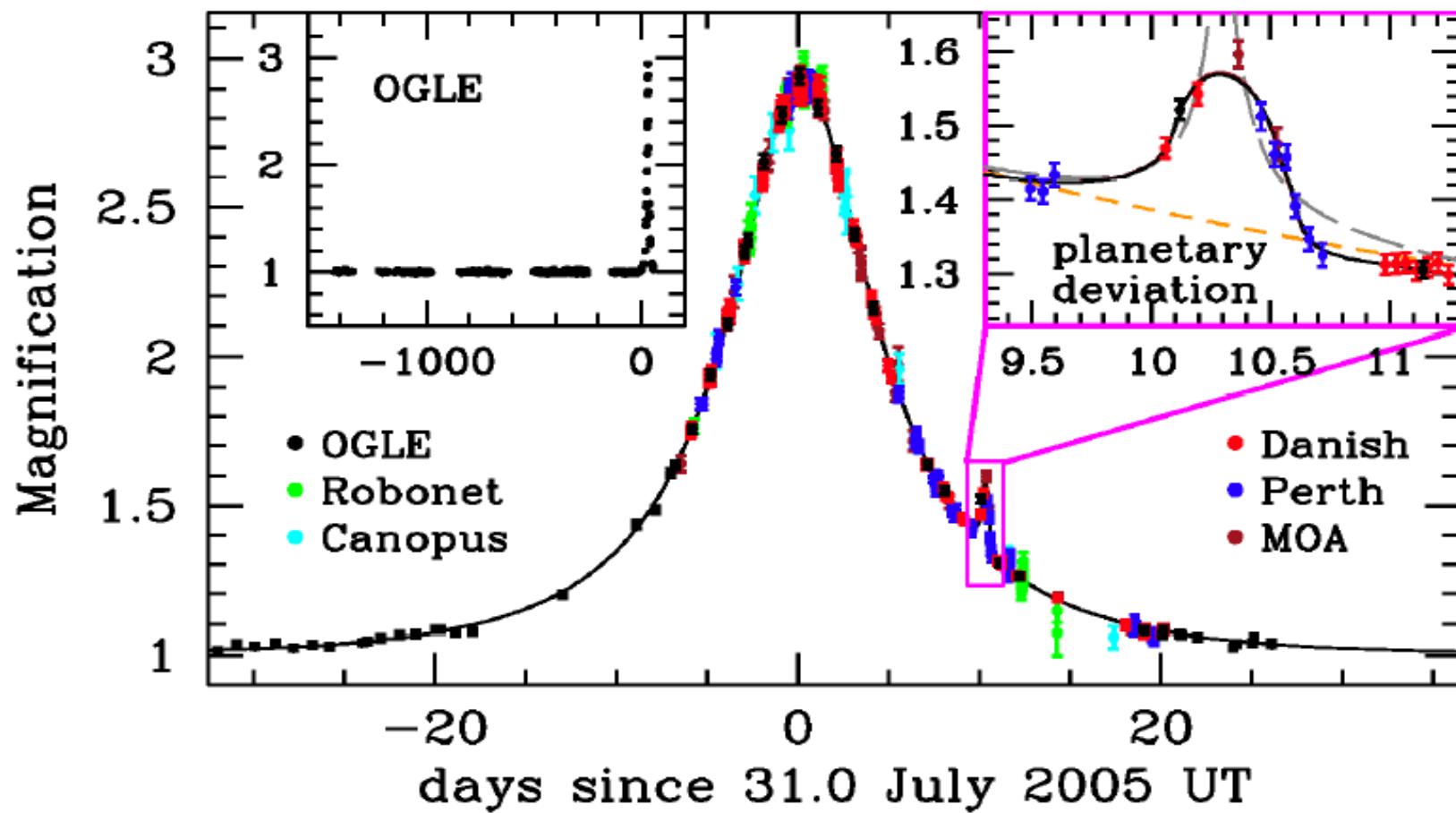
"It just shows that you can be a mother,
you can work full-time, and you can
still go out there and find planets."

Jennie McCormick

(Amateur Astronomer, Auckland, New Zealand)

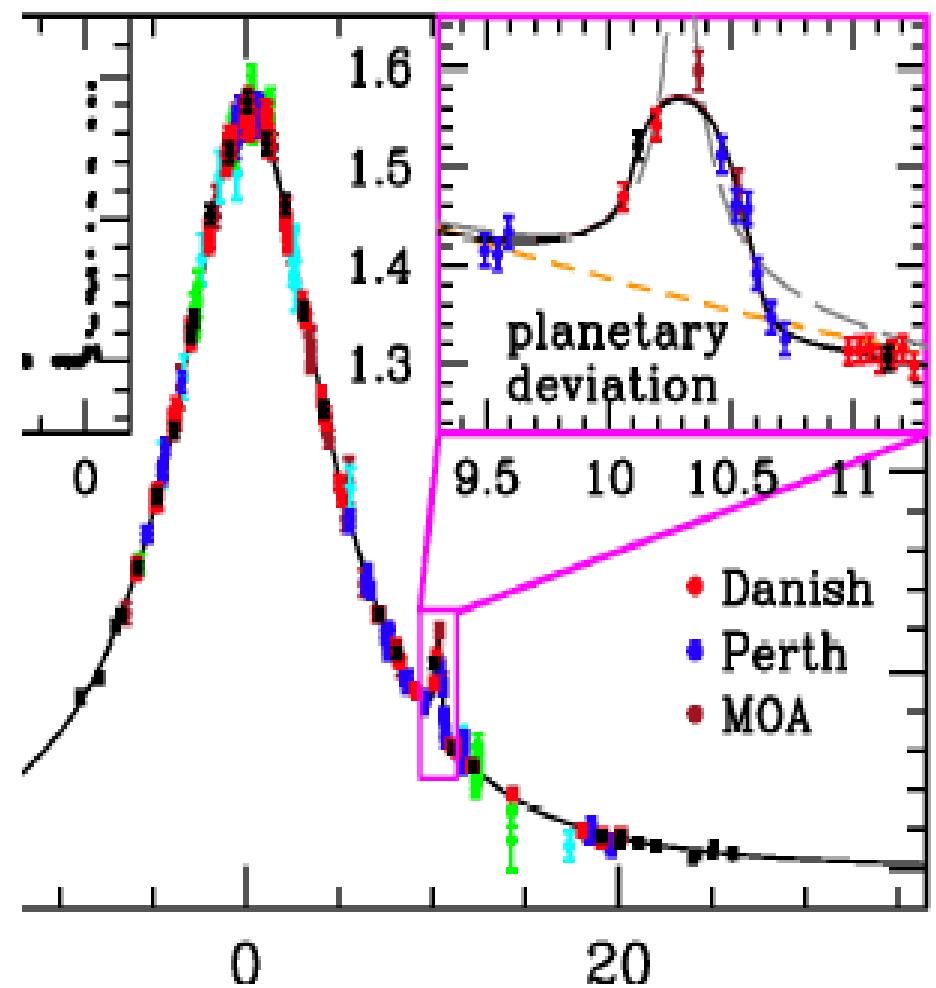
OGLE-2005-BLG-390

“Classical-Followup” Planetary Caustic

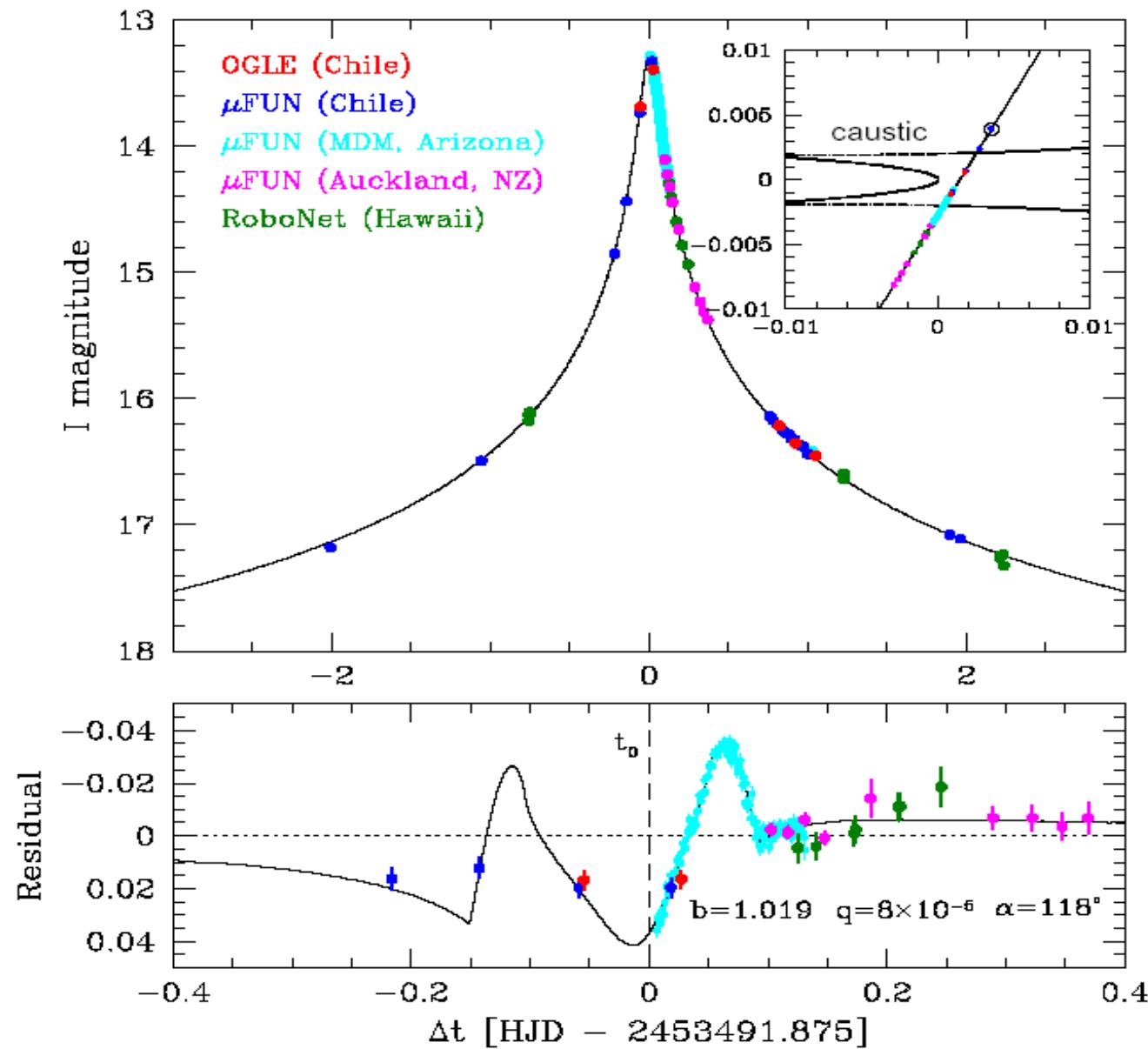


Planet/Star Mass Ratio: q

- Einstein time $t_E = 10d$
- Bump time $t_b = 0.3d$
- Bump height $A_b = 0.15$
- Mass ratio $q = (t_p/t_E)^2$
- $A_b = 2(t_p/t_b)^2$
- $= 2q(t_E/t_b)^2$
- $q = A_b(t_b/t_E)^2/2$
- $q = 7e-5$



OGLE-2005-BLG-169: COLD NEPTUNE in Hi-Mag Event

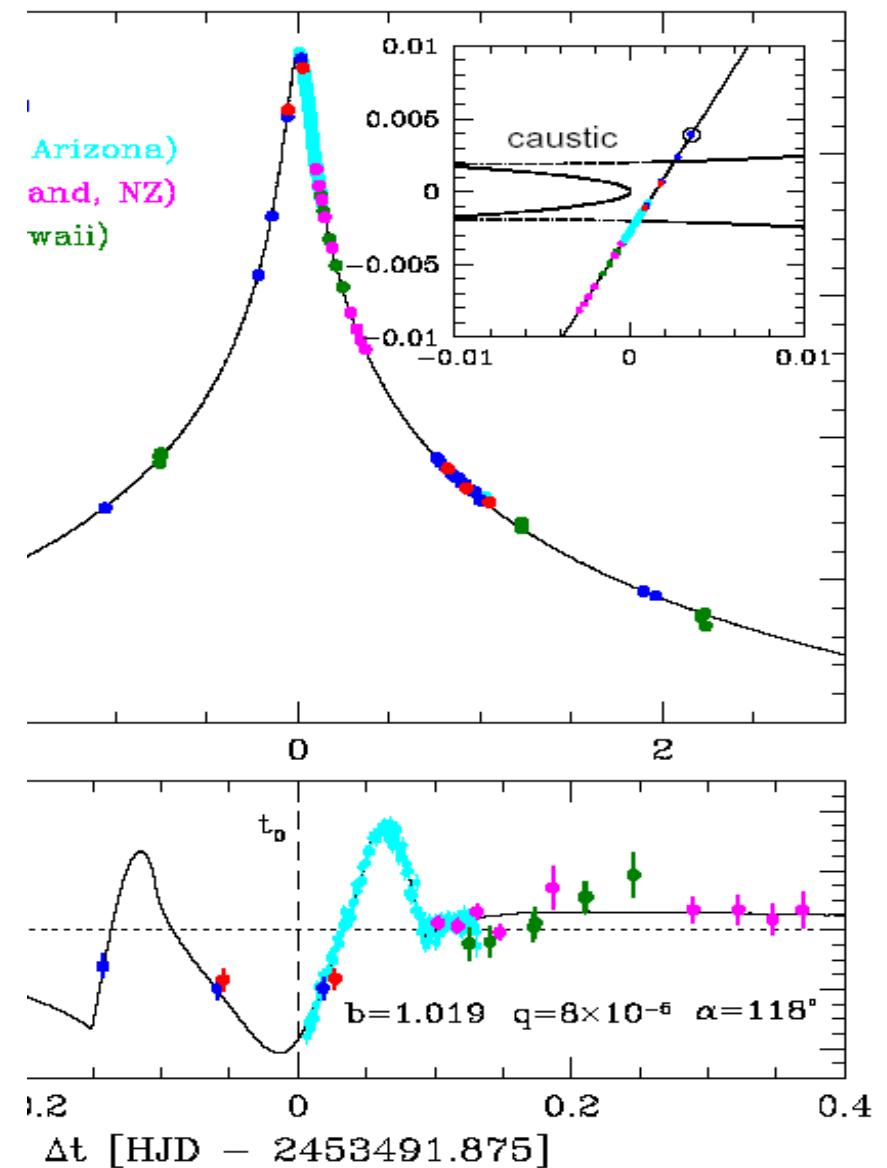


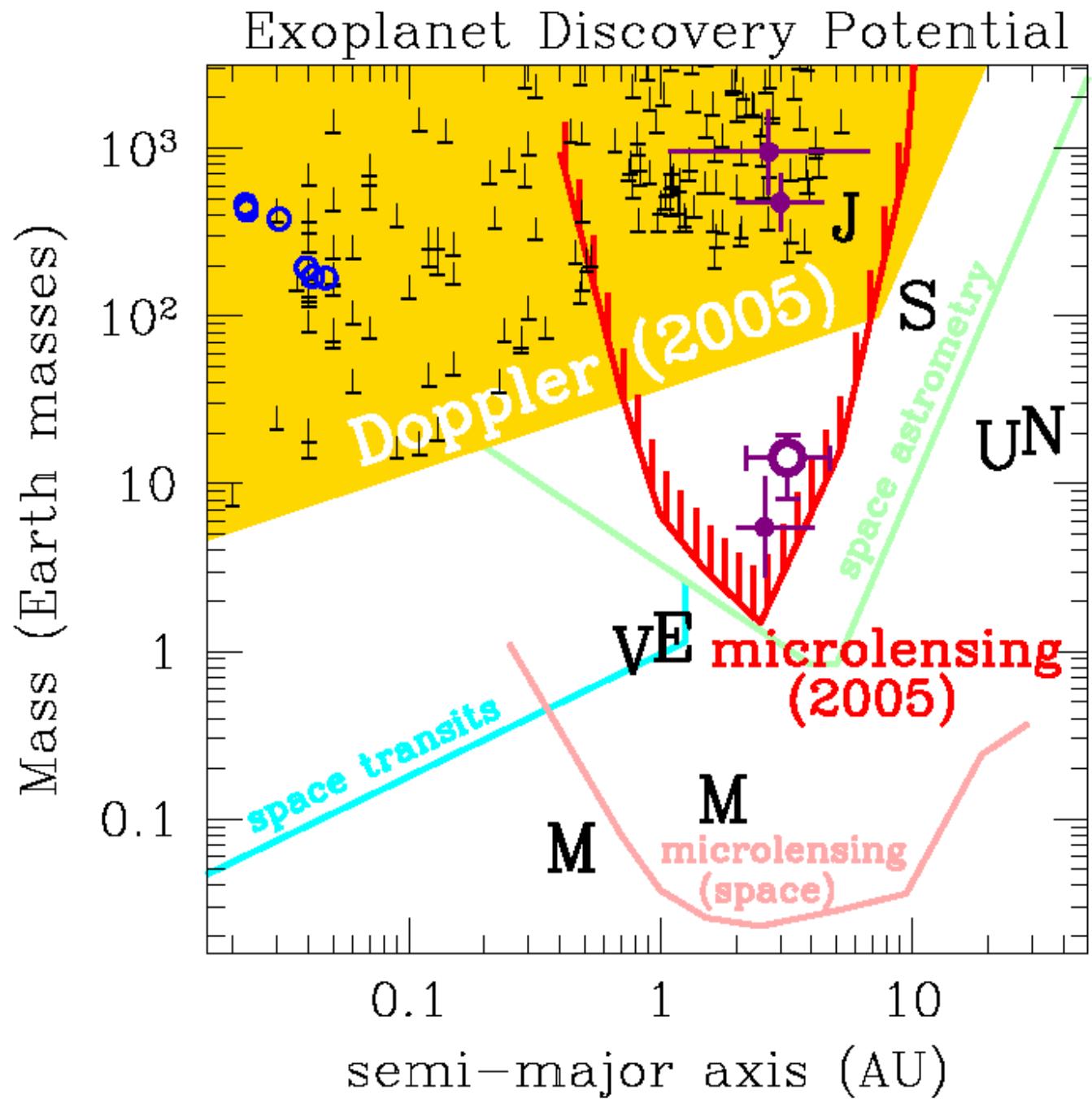
Deokkeun An



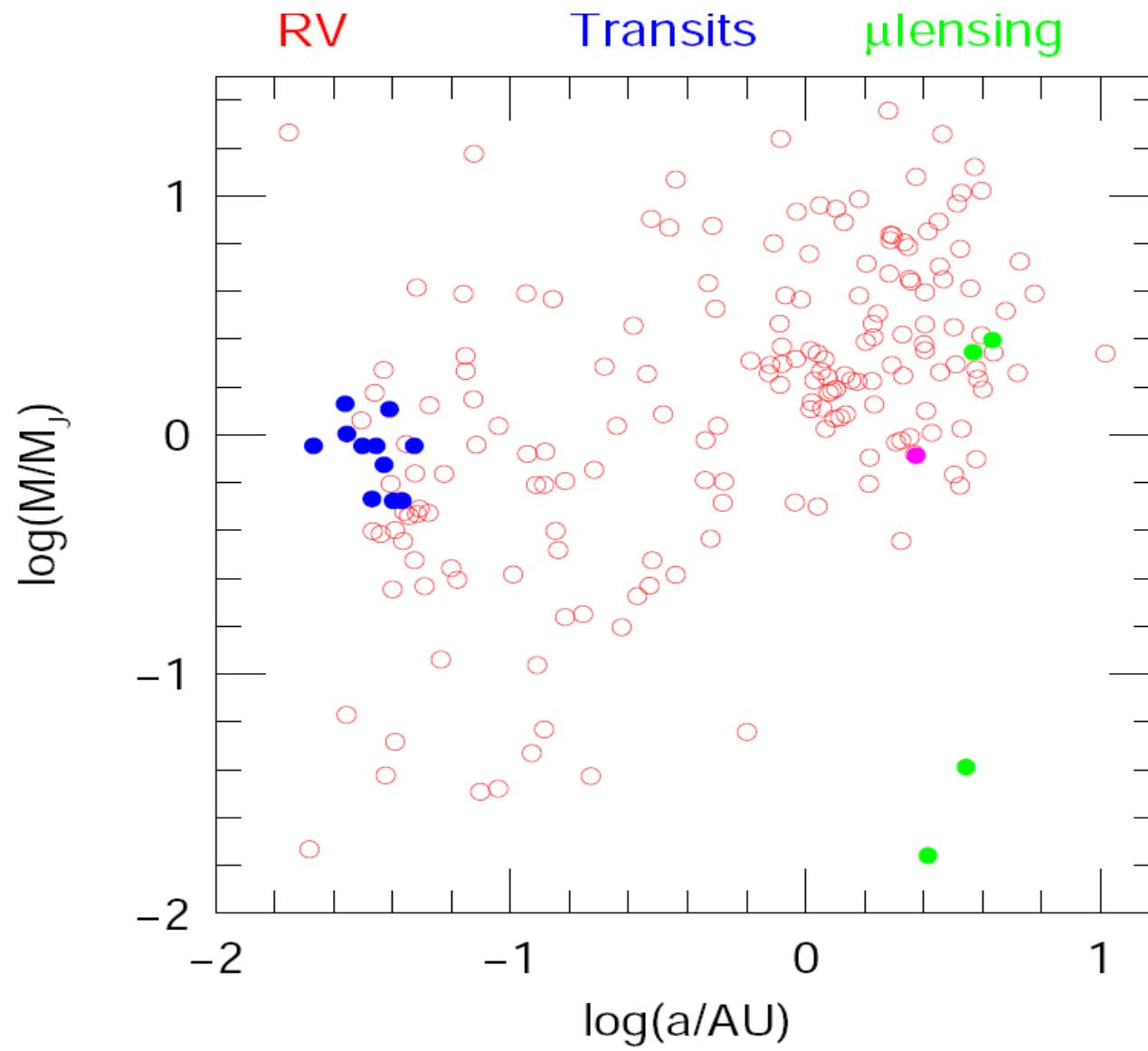
HOW DO WE KNOW IT'S A PLANET?

- 7 model parameters
 $t_0, u_0, tE, b, q, \alpha, \rho$
- 7 pronounced features
- -->3 from full curve
(height, width, center)
- -->4 from perturbation
(2 kink times, height
and width of bump)

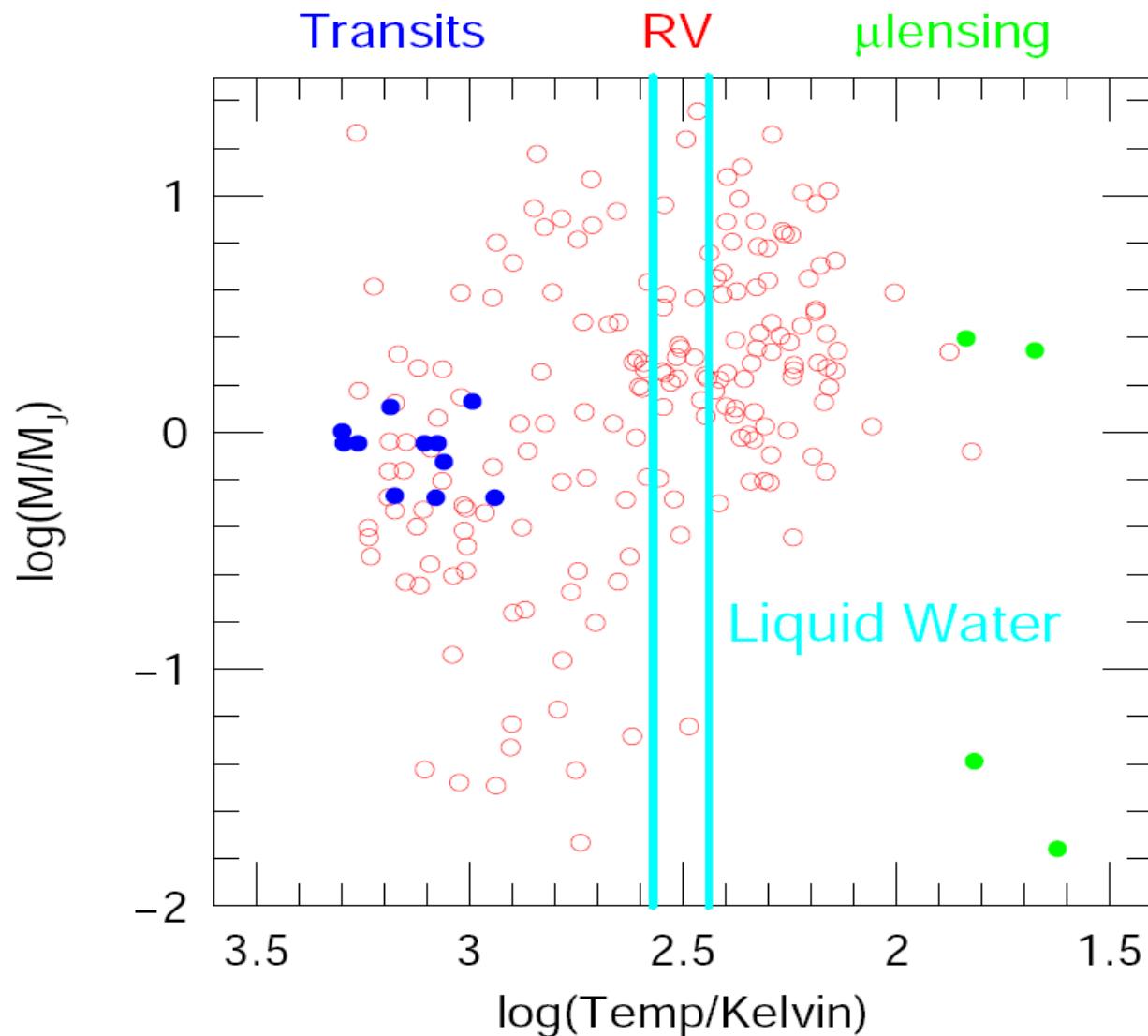




Conventional View



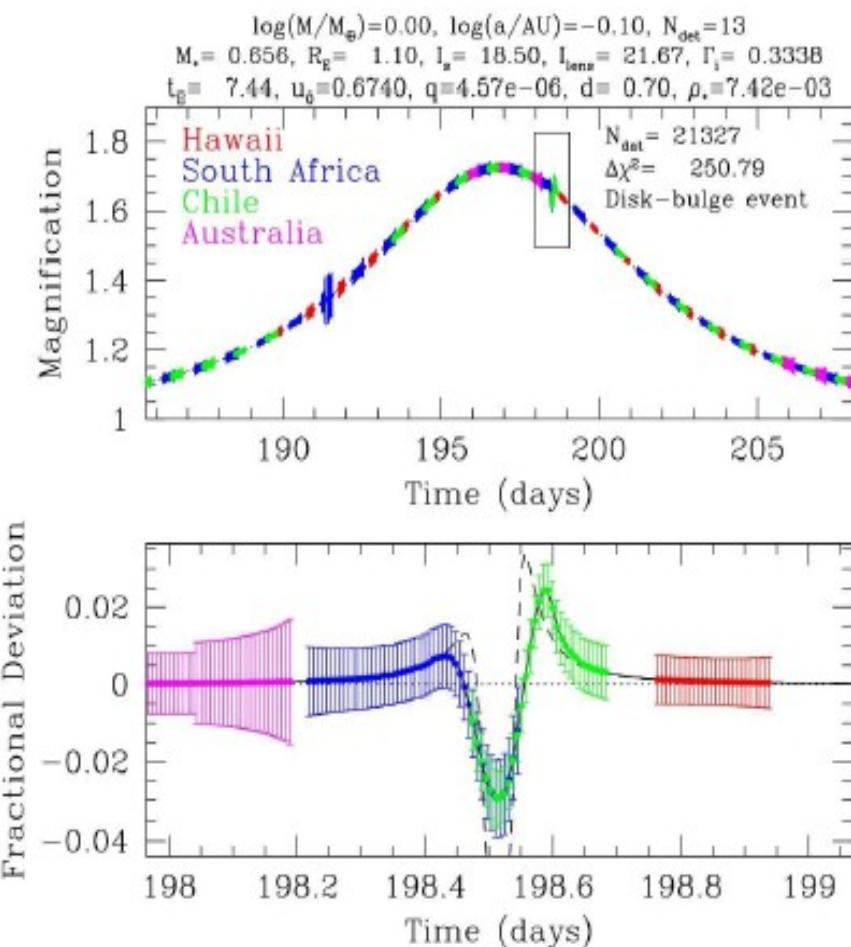
Unconventional View



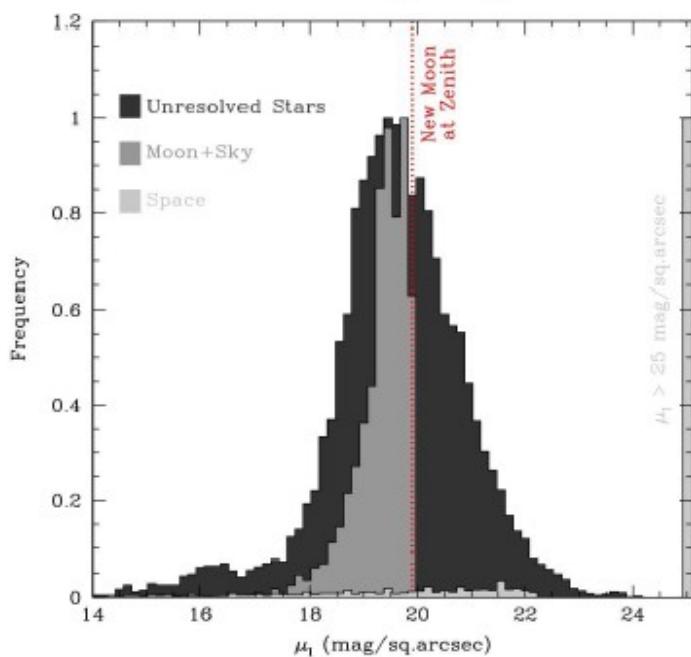
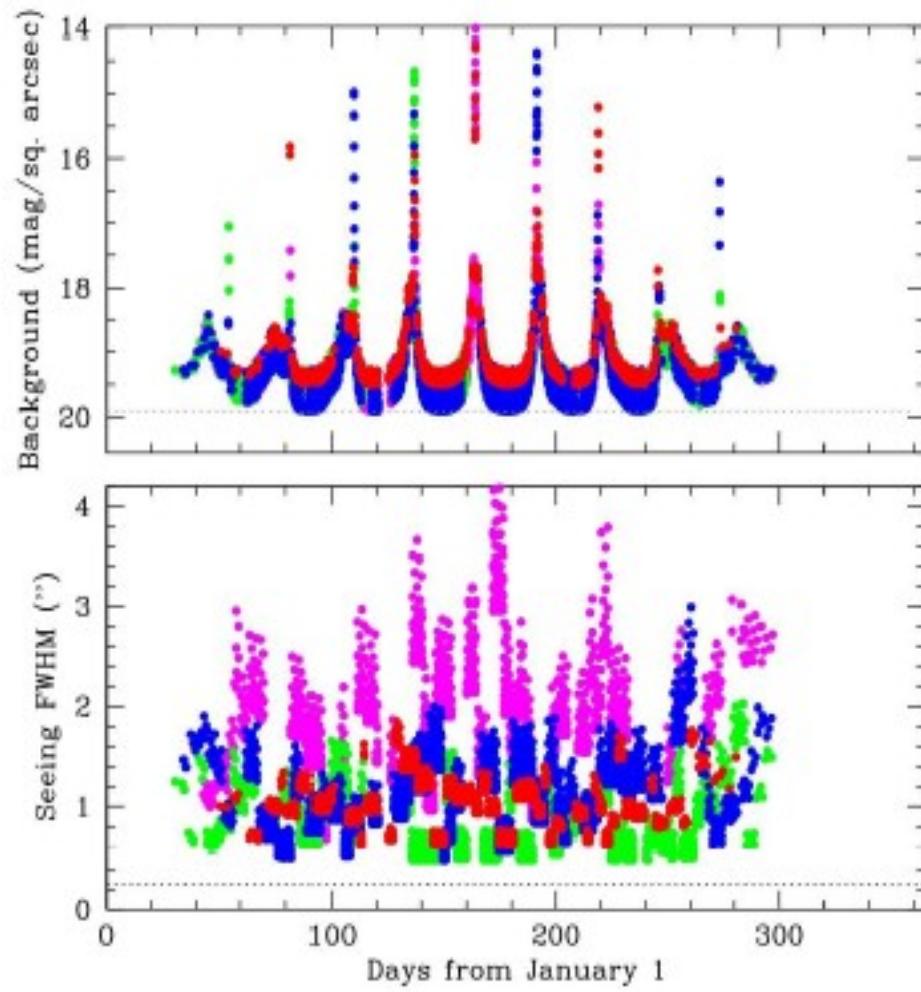
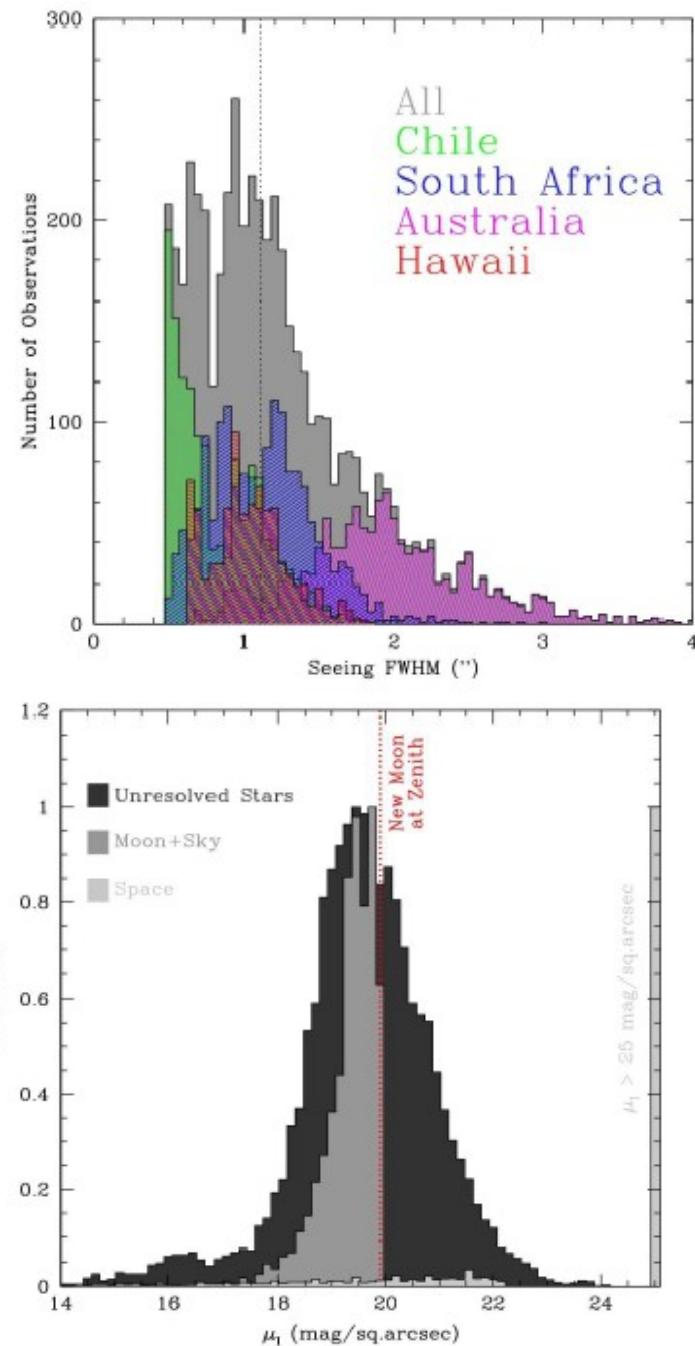
NextGen Microlensing Planet Search

Simulations by Scott Gaudi

- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics
down to systematics limit

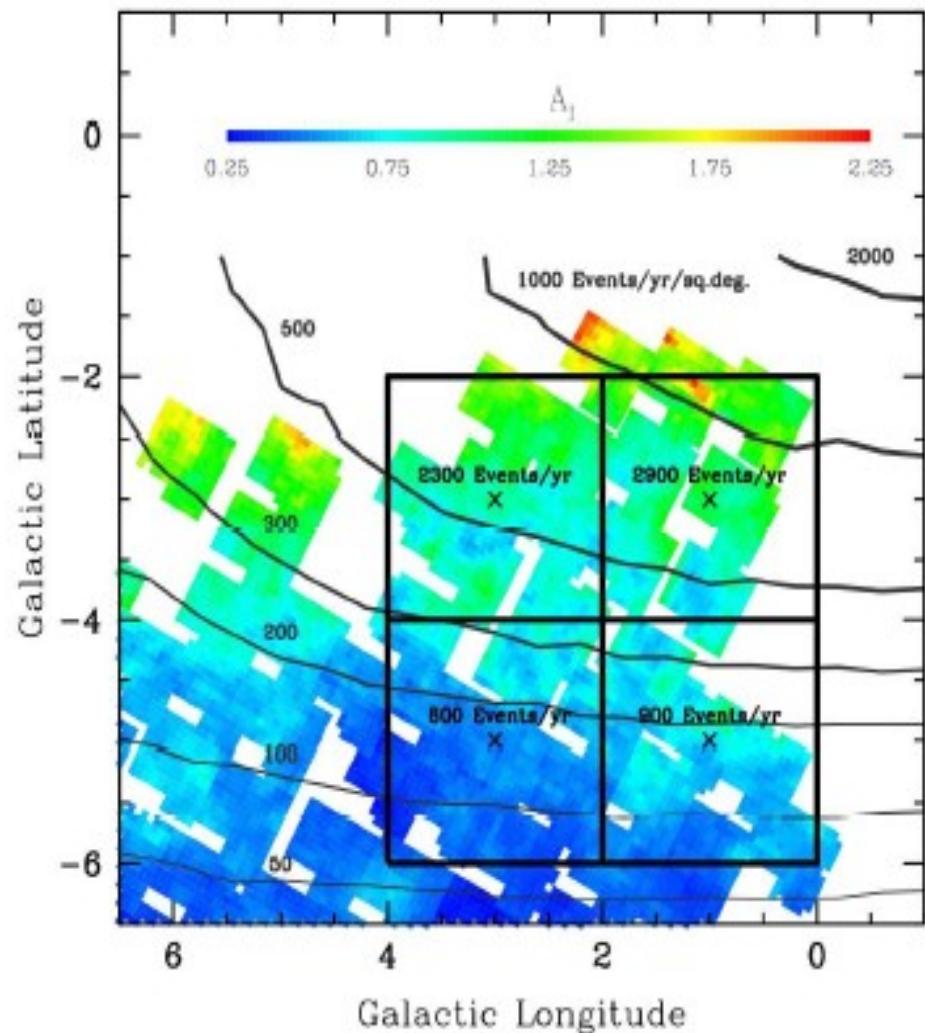


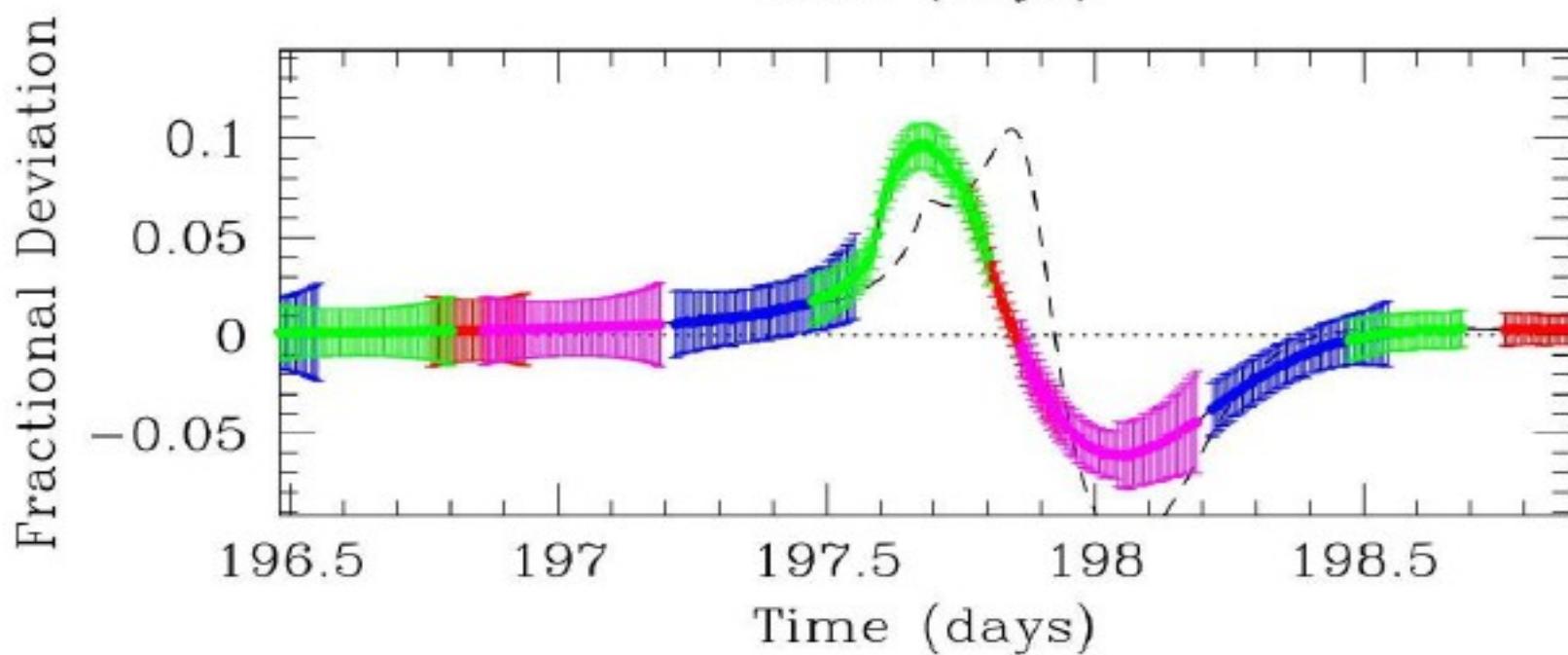
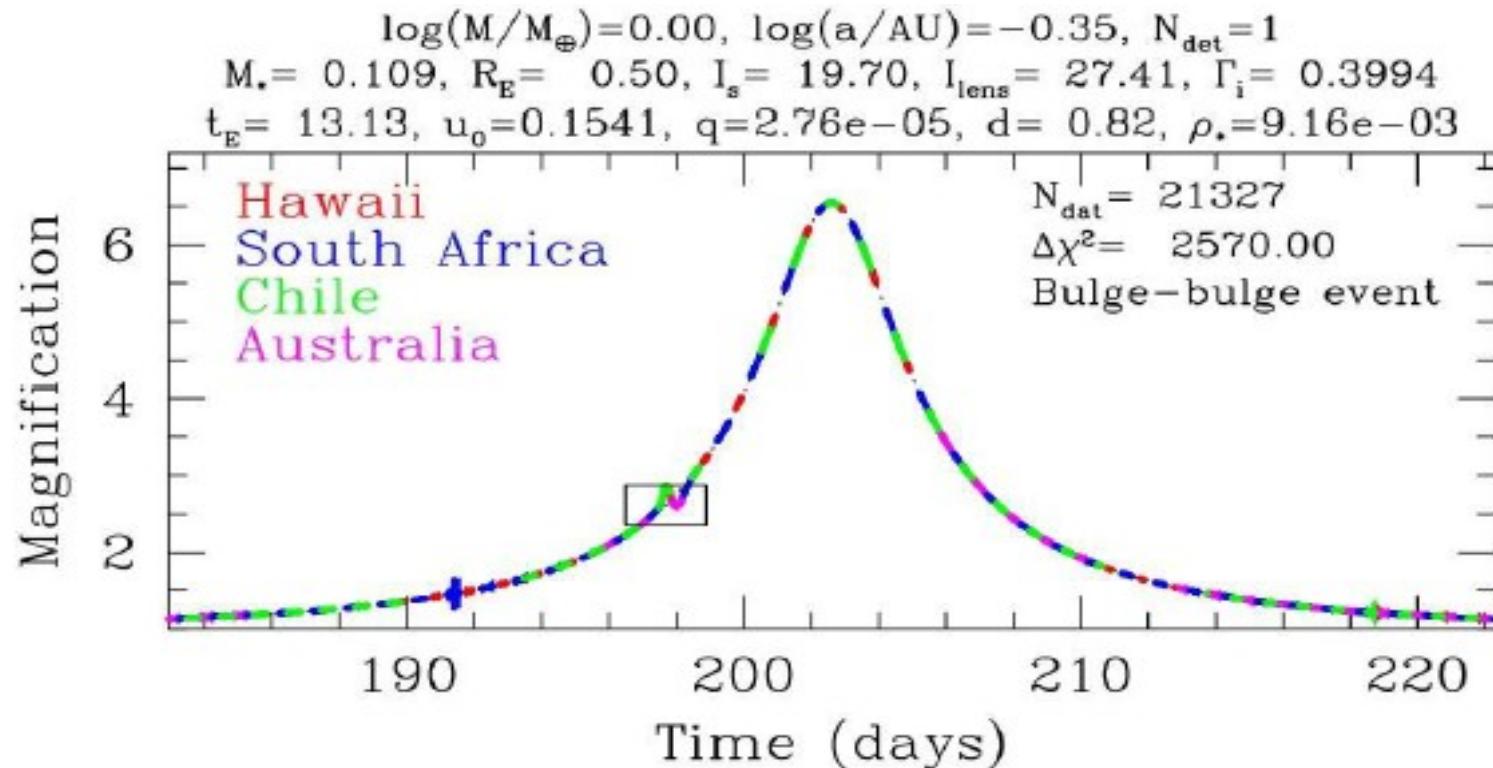
Simulation Ingredients (abridged)

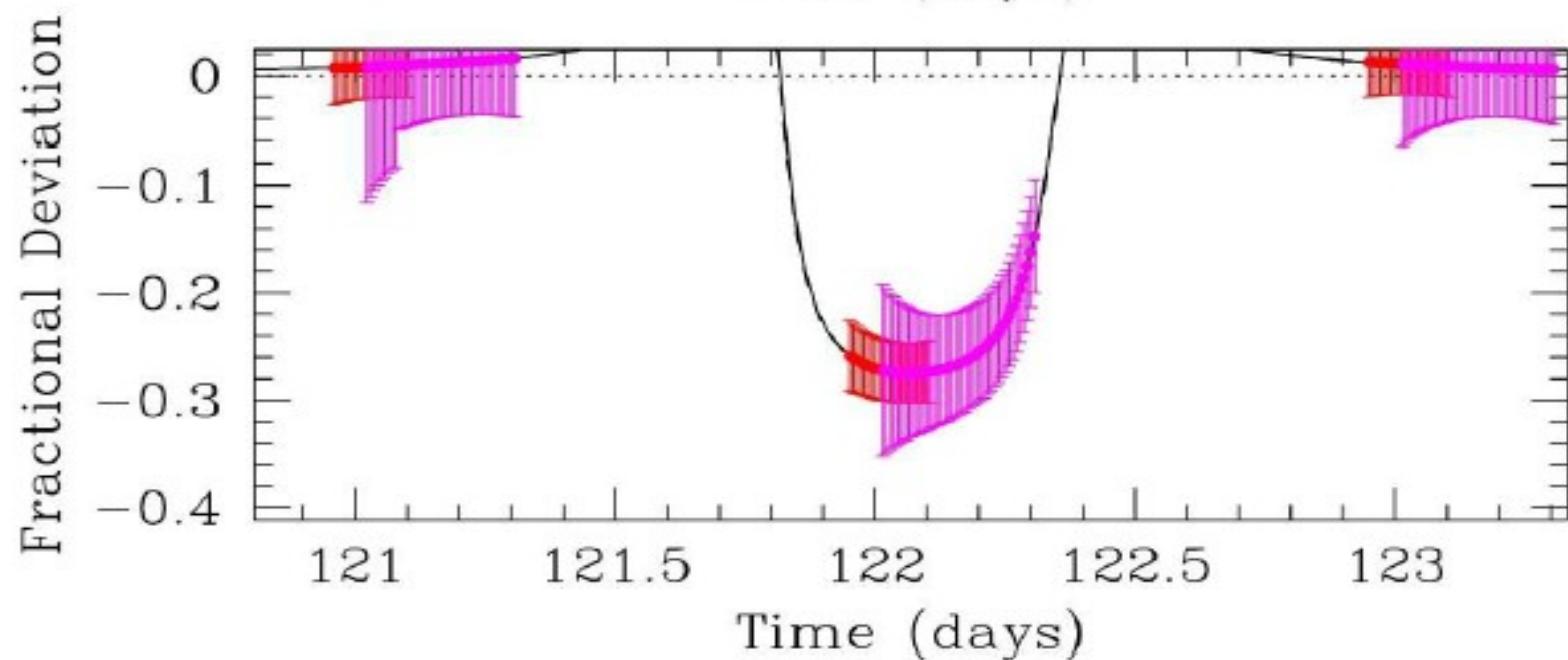
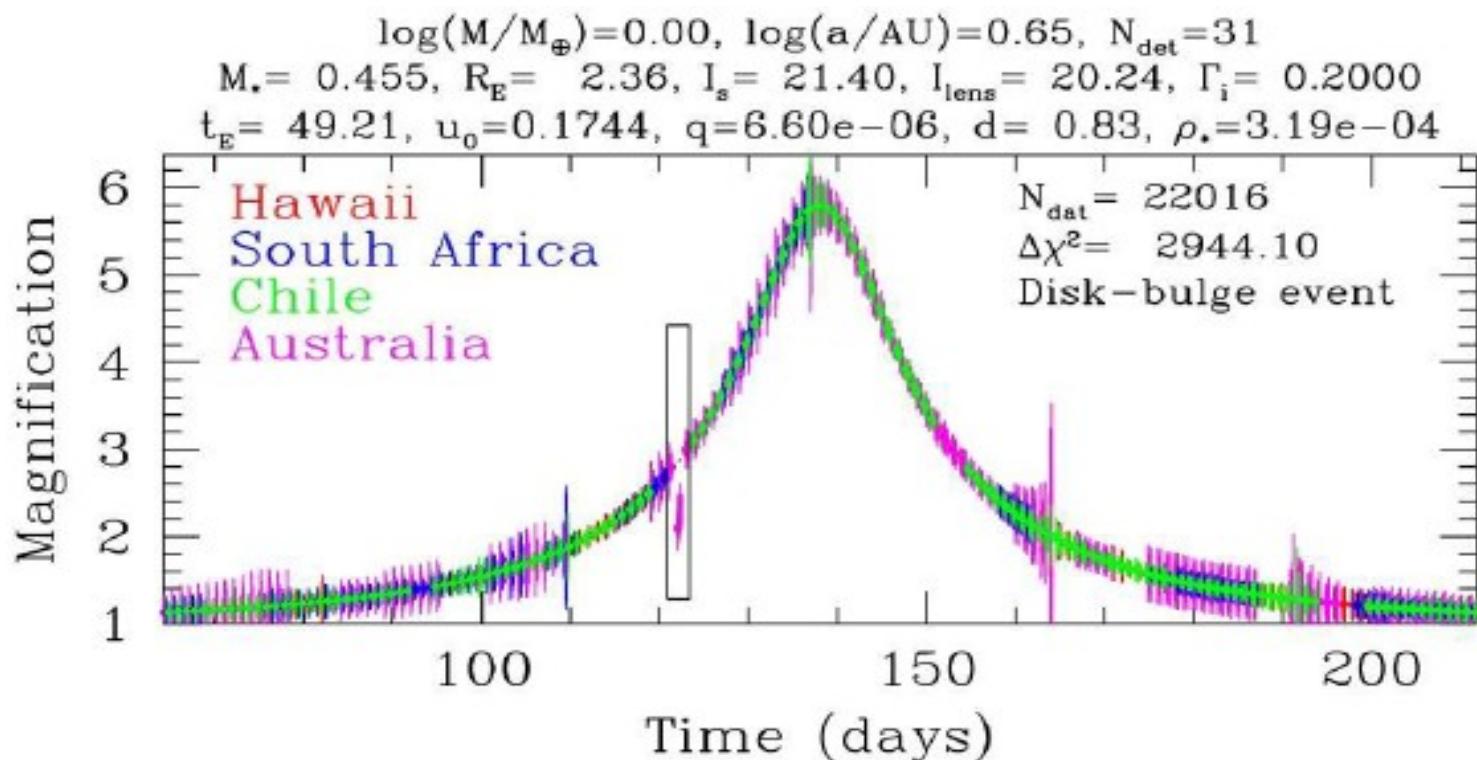


Target Fields

- Four Fields
 - $(l,b)=(1,-3)$
 - ~2900 Events/yr
 - $(l,b)=(3,-3)$
 - ~2300 Events/yr
 - $(l,b)=(1,-5)$
 - ~900 Events/yr
 - $(l,b)=(3,-5)$
 - ~800 Events/yr

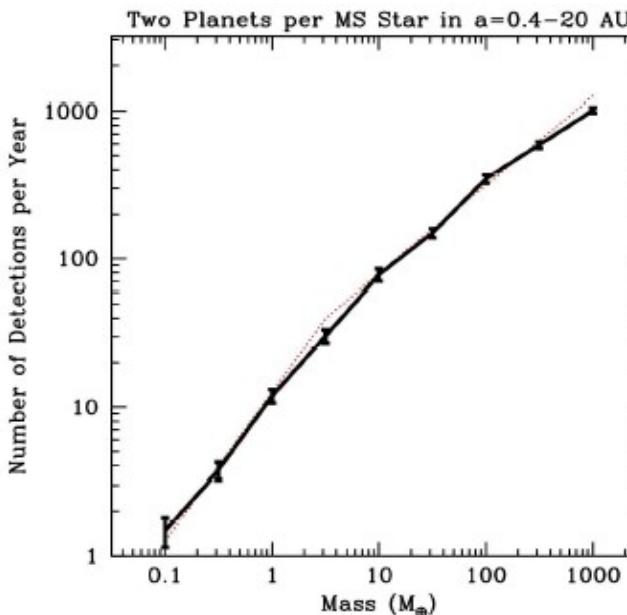
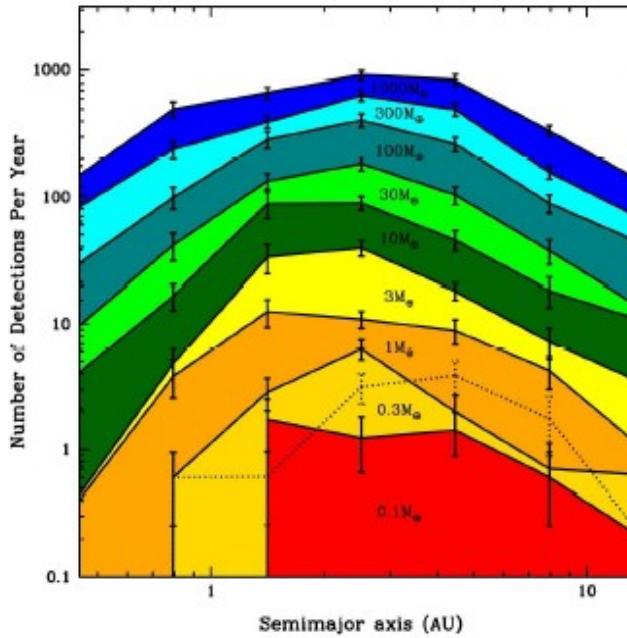


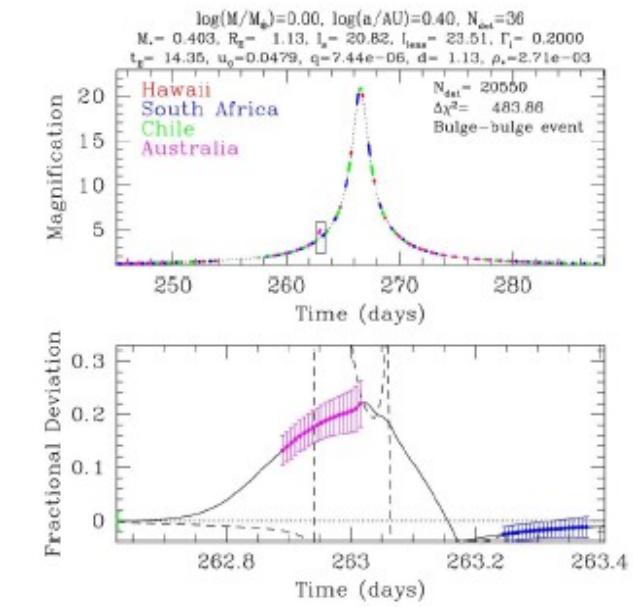
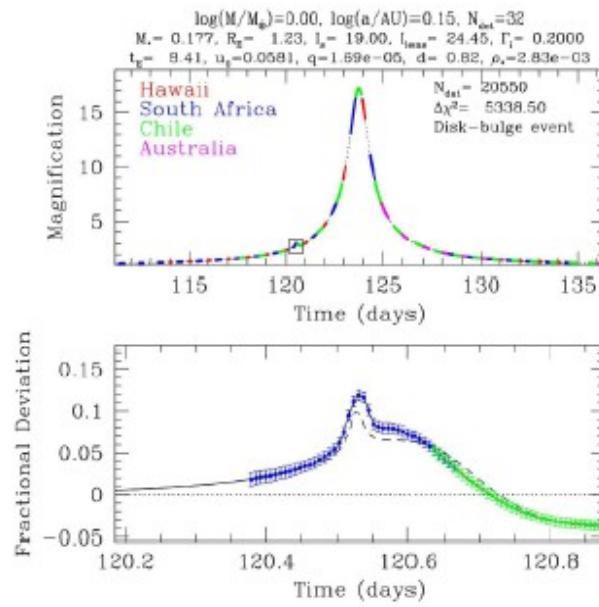
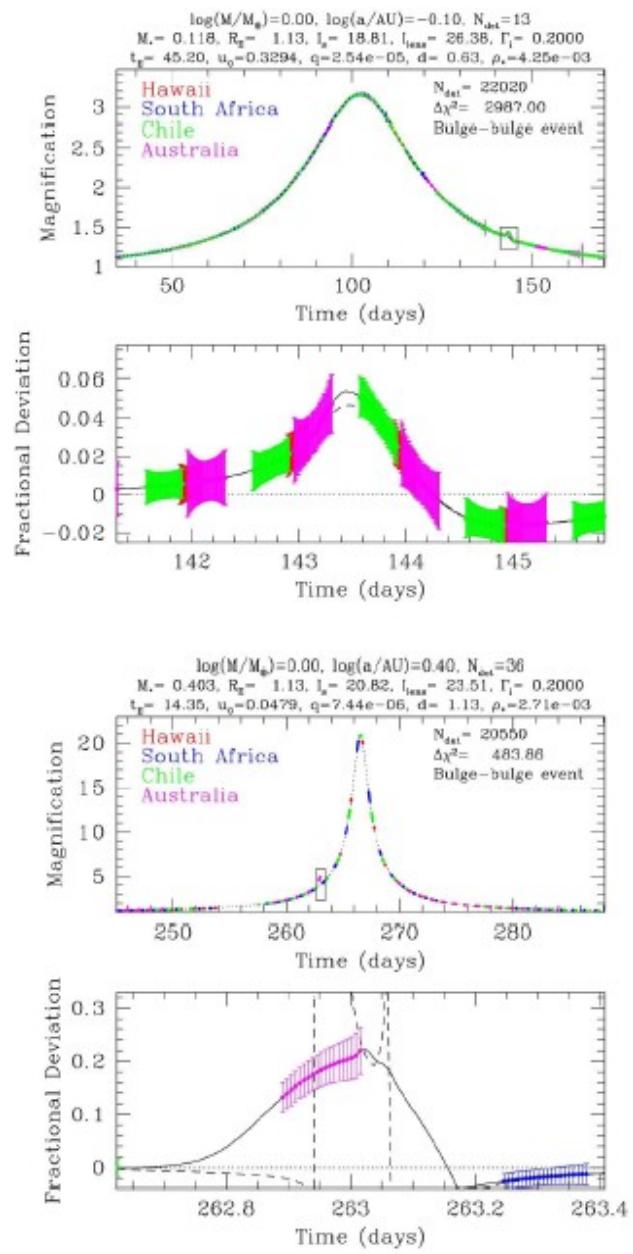
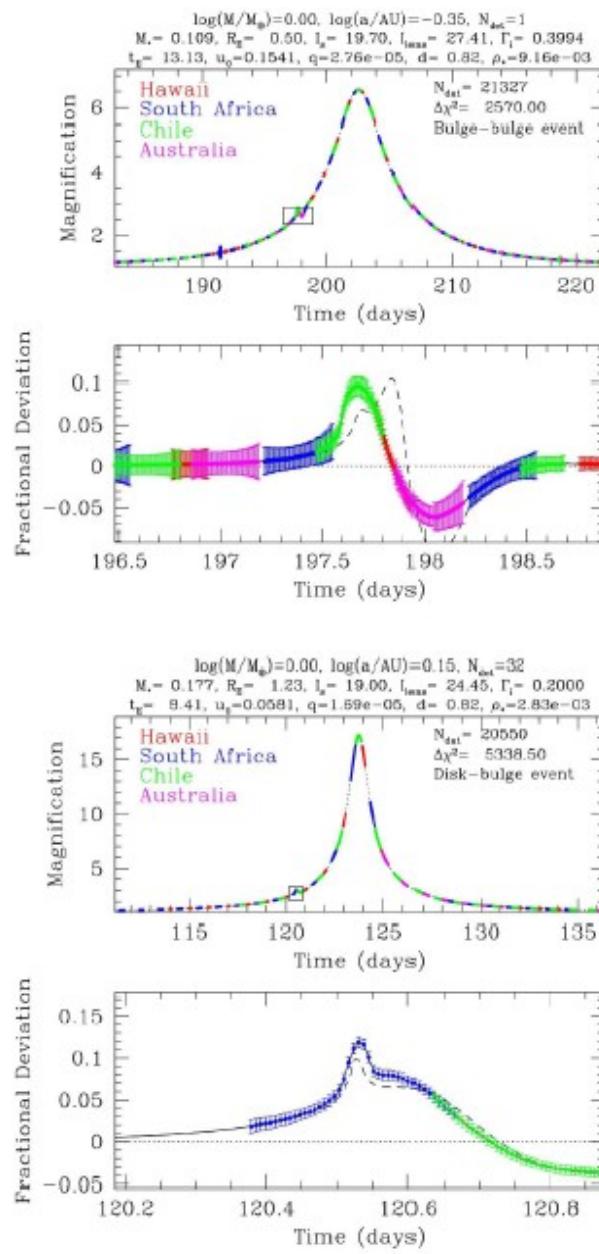


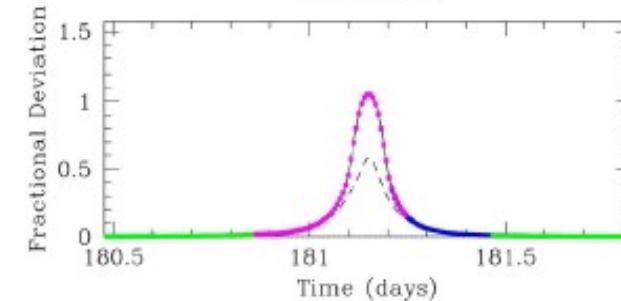
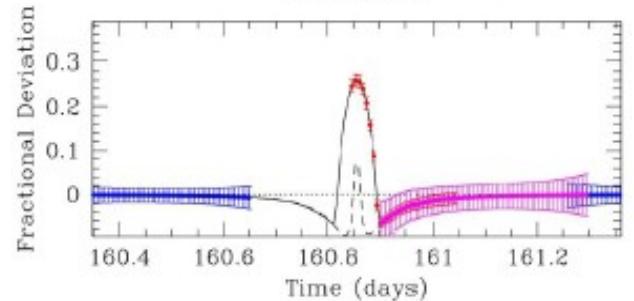
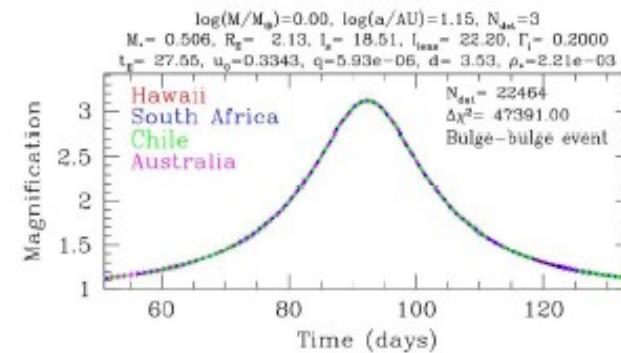
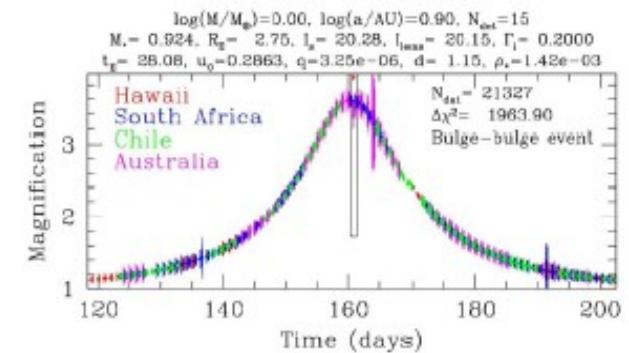


Baseline Results

- Simulate:
 - Mass:
 $\log(M/M_{\oplus}) = -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0$
 - Semimajor Axis:
 $\log(a/AU) = -0.35, -0.10, 0.15, 0.40, 0.65, 0.90, 1.15$
- Average over a
 - $-0.35 < \log(a/AU) < 1.15$
 - Two planets per star
- Scaling with Mass:
 - $N \propto M$ for $M < 3M_{\oplus}$
 - $N \propto M^{0.6}$ for $M > 3M_{\oplus}$







Summary of Baseline Results

log(a/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr ⁻¹)	0.4±0.4	3.8±1.2	12.5±3.1	10.9±1.7	8.8±1.9	4.3±1.2	1.0±0.7

Every MS star has one Earth-mass planet

log(a/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr ⁻¹)	0	0.6±0.3	0.6±0.4	3.1±0.9	3.9±1.2	1.8±0.9	0.2±0.2

Every MS star has one Earth mass ratio planet

log(M/M _⊕)	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Γ (yr ⁻¹)	1.5±0.3	3.7±0.5	12±1	30±3	78±8	150±10	350±20	590±30	1012±40

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU

Initiatives

- **MOA**: Existing 1.8m, 2.2 sq.deg telescope (NZ)
- **OGLE**: Funded to upgrade their 1.3m telescope to 1.4 sq.deg. (Chile)
- **KOREA**: In national competition for \$10M, to build 2 X 1.3m, 4 sq.deg telescope in Africa
- **OSU**: Committed to \$0.5M for NextGen camera
- **OTHER**: Germany, China ... ???

Approach: Threshold + Upgrades

- **THRESHOLD:** Major new telescope in Africa joined with existing/upgraded MOA and OGLE telescopes
- **POTENTIAL UPGRADES:**
 - Additional 2m/4sq.deg. telescope (Chile?)
 - Participation of other widefield telescopes e.g. PanStars (Hawaii), SkyMapper (Australia)

Microlensing Advantages

- Equally sensitive to planets around all stars
- Strong signal down to Mars-mass planets
- Sensitivity falls proportional to planet mass
- Sensitive at all separations $>\sim 0.5$ AU
- Most sensitive to planets just beyond snow line
- Sensitive to free-floating planets
- Most events reasonably well-characterized

Microlensing Challenges

- ORGANIZATION
 - 1) 2 search teams on 2 different continents
 - 2) 20 Follow-up observatories on 5.5 continents
 - 3) Round-the-clock coordination of observations
- MATHEMATICS
 - 1) Theoretical Insights into “lens equation”
 - 2) Applied math for modeling

Microlensing Prospects

- NextGen experiments have clear path to detect dozens—hundreds of planets
- Major niches:
 - 1) Beyond Snow Line
 - 2) Free Floaters
 - 3) Earth-Mass Planets
 - 4) Planets around M-dwarfs/BDs